Report

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Visual and Motor Cortices Differentially Support the Translation of Foreign Language Words

Highlights

- Learning foreign words with gestures or pictures outperforms verbal learning
- Learning foreign words with self-performed gestures leads to the best learning outcome
- Specialized visual and motor areas represent auditory foreign words after learning
- Classifier accuracy in visual and motor cortices predicts translation performance

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In Brief

Mayer et al. show that learning foreign vocabulary is more efficient if learners perform gestures while learning, in contrast to more conventional learning strategies. The neuroimaging results imply that after such gesture-enriched learning, vocabulary translation is facilitated because of the recruitment of specialized visual and motor areas.

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Report

Visual and Motor Cortices Differentially Support the Translation of Foreign Language Words

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Summary

At present, it is largely unclear how the human brain optimally learns foreign languages. We investigated teaching strategies that utilize complementary information ("enrichment"), such as pictures [1] or gestures [2], to optimize vocabulary learning outcome. We found that learning while performing gestures was more efficient than the common practice of learning with pictures and that both enrichment strategies were better than learning without enrichment ("verbal learning"). We tested the prediction of an influential cognitive neuroscience theory that provides explanations for the beneficial behavioral effects of enrichment: the "multisensory learning theory" [3, 4] attributes the benefits of enrichment to recruitment of brain areas specialized in processing the enrichment. To test this prediction, we asked participants to translate auditorily presented foreign words during fMRI. Multivariate pattern classification allowed us to decode from the brain activity under which enrichment condition the vocabulary had been learned. The visual-object-sensitive lateral occipital complex (LOC) represented auditory words that had been learned with pictures. The biological motion superior temporal sulcus (bmSTS) and motor areas represented auditory words that had been learned with gestures. Importantly, brain activity in these specialized visual and motor brain areas correlated with behavioral performance. The cortical activation pattern found in the present study strongly supports the multisensory learning theory [3, 4] in contrast to alternative explanations. In addition, the results highlight the importance of learning foreign language vocabulary with enrichment, particularly with self-performed gestures.

Results

In experiment 1, adults learned words of a foreign language [2] by hearing the words and their translations (Figure 1A, "learn"; Supplemental Experimental Procedures) under three conditions (Figure 1B). The first two conditions were enrichment strategies: (1) participants performed gestures symbolic to the word meaning (self-performed gestures) and (2) copied the outline of a picture illustrating the word meaning (copied pictures). In a control condition (3), participants learned without enrichment (no enrichment), which is a common way of teaching foreign language vocabulary known as verbal learning [7]. Learning outcome was monitored by paper-and-pencil translation tests at several time points (Figure 1A, "test"). After the learning week, we investigated blood-oxygenation-level-dependent (BOLD) responses elicited by the foreign words during a translation task. In this task, participants first heard an auditory foreign word while the screen remained black. Subsequently, participants saw a response screen with four written alternative translations of the foreign word. Participants were required to choose the correct translation (Figure 1C). We used multivariate pattern analysis (MVPA) [8–11] on BOLD responses elicited by the auditorily presented words (Figure 1C). This analysis method allows to test whether we could decode under which learning condition the word had been learned based on the pattern that the auditory words elicit across multiple voxels (for details, see the Supplemental Results).

Specialized Visual and Motor Areas Represent Auditory Foreign Words after Learning

As predicted by the multisensory learning theory [3, 4], visual and motor areas were informative about the learning conditions. A classifier trained to discriminate BOLD responses to auditory words learned with gestures and words learned without enrichment (gesture classifier) showed significant classification accuracy in a visual area that processes biological motion (left bmSTS), and in the left premotor cortex (PMot; Figure 2A and Tables S1 and S2). For a classifier trained to discriminate BOLD responses to words learned with pictures and words learned without enrichment (picture classifier), we found significant classification accuracy in a visual area that processes objects (right anterior LOC; Figure 2B and Tables S1 and S2).

Classifier Accuracy in Visual and Motor Cortices Predicts Translation Performance

Critically, if representations of foreign vocabulary in visual and motor areas improve learning outcome, we would expect correlations between brain responses and behavioral improvement caused by the enrichment. To measure the behavioral improvement, we calculated enrichment-benefit scores for each participant: the "gesture-benefit" score was the translation accuracy for words learned with gestures minus words learned without enrichment. The "picture-benefit" score was the translation accuracy for words learned with pictures minus words learned without enrichment. Correlations between the gesture benefit and gesture classifier during fMRI were significant in the right bmSTS and the left motor cortex (Figure 2C and Table S1; Supplemental Results). There was a trend for a correlation between the picture benefit and picture classifier in the left anterior LOC (Figure 2D and Table S1). These correlations showed that a higher enrichment benefit is associated with a more distinct neuronal activation pattern in sensory and motor areas for words learned with enrichment and words learned without enrichment. Such a finding is in accord with the multisensory learning theory [3, 4] because it implies that a more precise and consistent neuronal representation in specific sensory and motor areas is associated with the increased learning performance induced by enriched foreign language learning.

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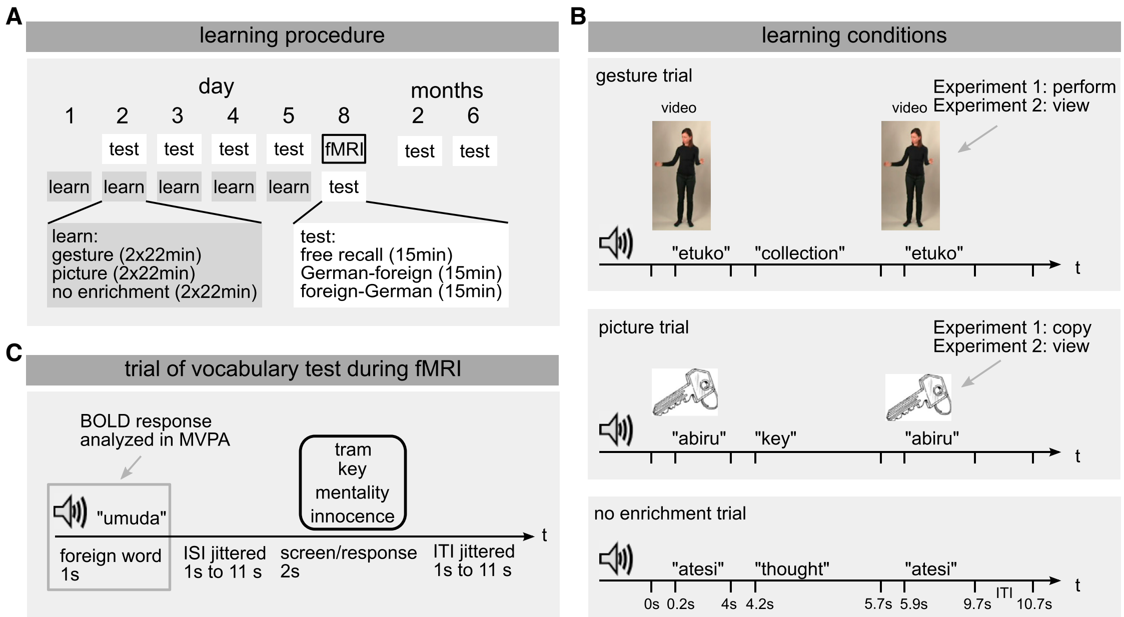

Figure 1. Experimental Procedure

(A) Participants learned foreign language words (“learn”) and completed translation tasks as well as free-recall tasks (“test”) in groups of seven to eight participants to emulate a classroom setting. Day 8 was the translation task with fMRI.

(B) Learning. In all conditions, participants heard a foreign word, the translation, and the foreign word again. For the gesture and picture conditions, gestures or pictures were presented together with the foreign word. In the no-enrichment condition, there was no additional information presented. In experiment 1, participants performed the gestures shown in the video and copied the outline of the pictures with the right index finger in the air (motor tasks). In experiment 2, participants viewed gestures and pictures (no motor tasks).

(C) FMRI. Participants heard a learned foreign language word and subsequently saw a screen with translations. Participants selected the correct translation via button press. We analyzed the BOLD responses to the auditory foreign word. The inter-stimulus interval between the auditory word and the response screen was jittered between 1 s and 11 s with a mean of 2 s. In the fMRI, the participants additionally performed two functional localizers (not shown) that served to localize biological motion sensitive superior temporal sulcus (bmSTS) [5] and a visual object processing area (lateral occipital complex, LOC) [6]. Speaker icons indicate the auditory presentation of words. Umuda, etuko, abiru, and atesi were foreign words presented auditorily. ISI, inter-stimulus interval; ITI, inter-trial interval; BOLD, blood-oxygenation-level-dependent; MVPA, multivariate pattern analysis. English words in the figure were presented in German in the experiment. See also Table S4.

Learning Foreign Words with Self-Performed Gestures Leads to the Best Learning Outcome

We tested which enrichment strategy yielded the best learning outcome by measuring translation accuracy and enrichment-benefit scores for the paper-and-pencil translation tasks. For fMRI scanning, we had trained the participants to very good performance (Supplemental Experimental Procedures), so that there were no performance differences between the learning conditions on the paper-and-pencil translation task at the time of MRI scanning (day 8: $p > 0.44$; Table 1). Paper-and-pencil translation tasks conducted 2 months and 6 months post-learning revealed significantly better translation accuracy after learning with self-performed gestures than with copied pictures and no enrichment (1 × 3 ANOVAs with the within-subjects factor enrichment and the levels gesture, picture, no enrichment; 2 months post-learning: $F_{2,\ 38} = 8.77$, $p = 0.001$, $\eta_p^2 = 0.32$; 6 months post-learning: $F_{2,\ 26} = 10.10$, $p = 0.001$, $\eta_p^2 = 0.44$; Figure 3A, Table 1, and Figure S1A). This was surprising because enrichment in form of pictures is often used in teaching practice and has been shown to be effective for foreign language teaching [1, 12]. In a further experiment (experiment 2), we therefore tested whether our finding can be explained by the unusual task of copying pictures used in experiment 1. We employed the same paradigm as in experiment 1 (Figure 1). However, in order to emulate a more typical learning scenario for pictures, we only had participants view the enrichment (either gestures or pictures) during learning. Without motor tasks, the picture condition led to better translation accuracy than the other two conditions (1 × 3 ANOVAs with the within-subjects factor enrichment and the levels gesture, picture, no enrichment; day 8: $p > 0.14$; 2 months post-learning: $F_{2,\ 38} = 13.34$, $p < 0.001$, $\eta_p^2 = 0.41$; 6 months post-learning: $F_{2,\ 30} = 7.20$, $p = 0.003$, $\eta_p^2 = 0.32$; Figures 3B and S1B). At the brain level, we found similar results as in experiment 1. Classification accuracy was significant in the right anterior LOC for the picture classifier, and there was a correlation between gesture classifier and gesture benefit in the right bmSTS (Figure S2 and Tables S1 and S2). There was no evidence for involvement of motor areas in experiment 2. This was expected as there were no motor tasks during learning. In both experiments, the paper-and-pencil tests also included a free-recall task. We did not find enrichment benefits on this task. Therefore, here we focused on the results of the translation tasks only. For discussion of the free-recall results, see the Supplemental Results and Supplemental Discussion.

Next, we compared the behavioral findings *across* the two experiments (see the Supplemental Results). We used gesture-benefit and picture-benefit scores to investigate whether learning with self-performed gestures enhances translation accuracy to a larger extent than learning with viewed pictures or vice versa. We used a 2 × 2 mixed-design ANOVA with the within-subjects factor benefit (gesture benefit, picture benefit)

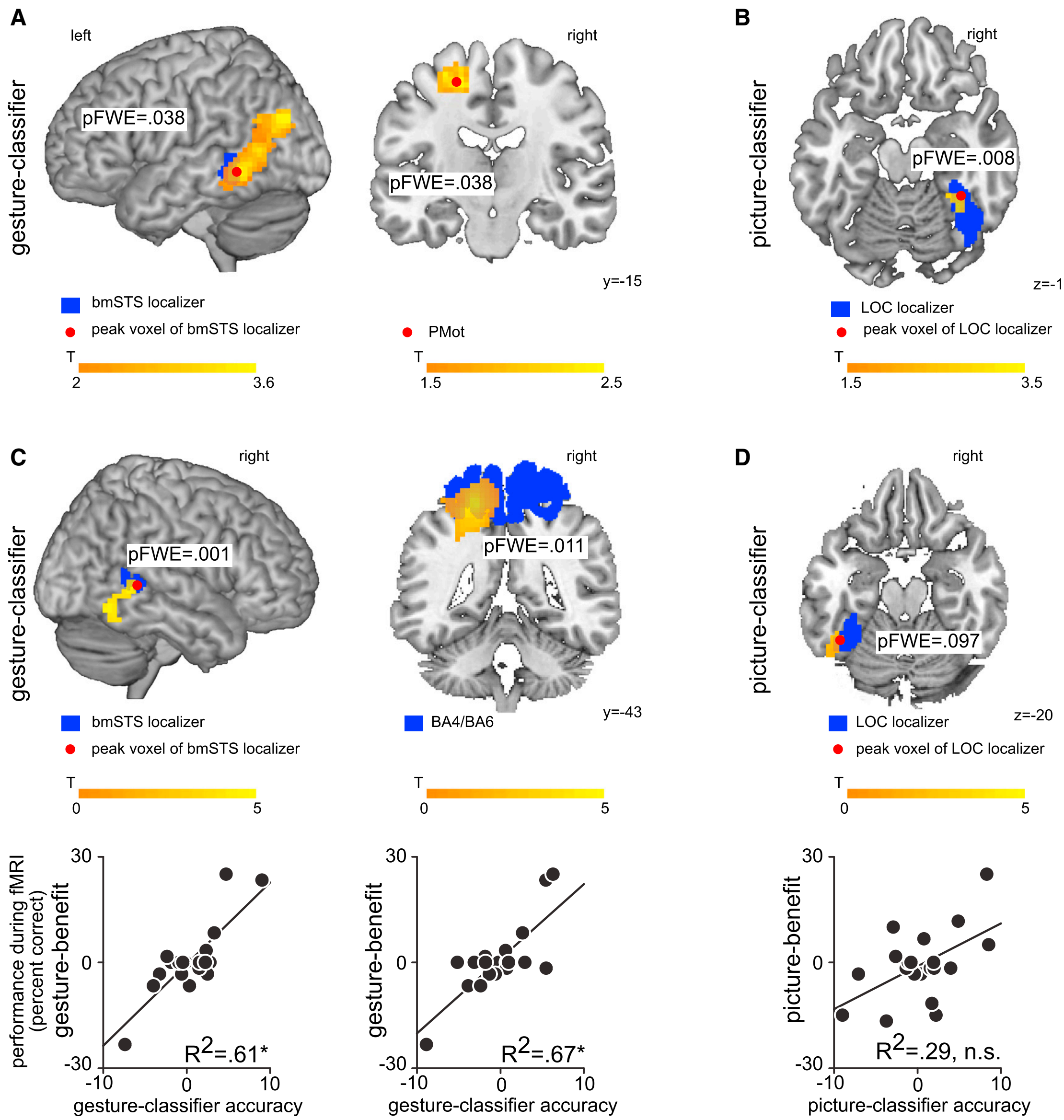

Figure 2. FMRI Results of Experiment 1: Motor Tasks

Biological motion superior temporal sulcus (bmSTS) [5] and lateral occipital complex (LOC) [6] were defined functionally with standard localizers. BA4/BA6 was defined anatomically based on an anatomical mask (Supplemental Results). The premotor cortex (PMot) coordinate was identified by Macedonia et al. [2]. Red dots indicate centers of spheres for region of interest (ROI) analyses. p values are familywise error (FWE) corrected for the ROI. In the scatter plots, each dot represents a participant. *$p < 0.05$. n.s., not significant. Classifier accuracies are mean centered and displayed in percentages.

(A and B) Motor and specific visual sensory cortex areas were informative about whether the auditorily presented word was learned with enrichment or not. An area in motor cortex and the visual bmSTS was informative about whether the auditory word was learned with gestures or without enrichment (yellow/orange; A). The LOC was informative about whether the auditorily presented word was learned with pictures or without enrichment (B).

(C and D) Positive correlation of classifier accuracy in bmSTS, motor cortex, and LOC with behavioral performance, i.e., the enrichment benefit. This benefit is the difference in translation accuracy between words learned with enrichment (gesture, picture) and words learned without enrichment (yellow/orange). There was a positive correlation of classifier accuracy in visual bmSTS and motor cortex with the gesture benefit (yellow/orange; C). There is a trend to significant positive correlation of classifier accuracy in the LOC with the picture benefit (yellow/orange; D).

See also Figure S2 for the results of experiment 2 and Tables S1–S3 and S5 for more details of the fMRI results.

and the between-subjects factor experiment (experiment 1, motor tasks; experiment 2, no motor tasks). The ANOVA revealed interactions of experiment and benefit (2 months post-learning: $F_{1,\ 38} = 38.82$, $p < 0.001$, $\eta_p^2 = 0.51$; 6 months post-learning: $F_{1,\ 28} = 22.44$, $p < 0.001$, $\eta_p^2 = 0.45$). There were no main effects ($Fs < 2.21$). We then evaluated the difference between gesture benefit in experiment 1 and picture benefit in experiment 2. We found that the benefit due to enrichment after learning with self-performed gestures was significantly larger than after learning with viewed pictures 6 months post-learning ($p < 0.05$, Tukey post hoc test; Figure 3C). This effect cannot be explained by performance differences in the no-enrichment conditions, because performance was similar in the no-enrichment conditions in the two experiments 2 and 6 months post-learning (Table 1; two-sampled t tests, $p > 0.99$). The results rather suggest that, in the long term, translation accuracy for vocabulary is

Table 1. Accuracies on the Translation Tasks during fMRI, 2 Months Post-learning, and 6 Months Post-learning

	Experiment 1		Experiment 2	
Condition	Percent Correct	SEM	Percent Correct	SEM
During fMRI				
Gesture	89.21	2.76	87.27	2.60
Picture	87.93	2.92	89.85	2.34
No enrichment	88.65	3.29	89.85	2.40
2 Months Post-learning				
Gesture	49.92	6.46	42.83	5.64
Picture	43.75	6.52	51.42	5.82
No enrichment	42.33	6.45	42.33	6.18
6 Months Post-learning				
Gesture	41.55	7.22	28.85	4.72
Picture	33.69	7.10	36.98	5.68
No enrichment	31.19	6.85	30.63	5.28

Experiment 1 (motor tasks): fMRI, n = 21; 2 months post-learning, n = 20; 6 months post-learning, n = 14. Experiment 2 (no motor tasks): fMRI, n = 22; 2 months post-learning, n = 20; 6 months post-learning, n = 16.

better when words are learned with self-performed gestures than with viewed pictures.

Discussion

Our results show that (1) both viewed pictures and self-performed gestures improve learning outcome with respect to verbal learning (no-enrichment condition) and (2) self-performed gestures improve learning outcome to a larger extent than viewed pictures, and the fMRI results suggest that (3) the beneficial effects of enrichment originate from specialized visual and motor areas.

The results of both experiments were in line with the predictions of the multisensory learning theory [3, 4]. We also checked whether the improved learning outcome could be explained by alternative mechanisms. For example, based on the "levels-of-processing theory" [13, 14], one could speculate that enrichment strategies boost learning because the encoding of the word meaning involves several levels (e.g., because the auditory word was learned together with a symbolic or iconic gesture). Typical levels-of-processing effects are, for example, enhanced memory for words in the native language when participants perform semantic judgments on these words (e.g., whether the word is emotional or not), in contrast to orthographic judgments (whether the word contains a "p") [13, 15]. These enhanced memory effects due to semantic-encoding tasks have been associated with increased activation in frontal and temporal areas [14]. In our study, we did not find consistent evidence for the involvement of these or other areas that have been associated with "semantic" processing [16] (Table S3). A lack of consistent activation patterns in other areas besides the identified motor and sensory areas does not entirely rule out alternative mechanisms. Furthermore, we do not assume that translation tasks are performed without the contribution of areas involved in semantic processing. We, however, speculate that these areas are involved in the translation tasks to the same extent across all learning conditions [17] and that their involvement is independent of any enrichment benefit.

Our behavioral findings showed that learning with self-performed gestures leads to the best long-term vocabulary-learning outcome for translation tasks. Other studies have investigated foreign vocabulary learning with gestures (self-performed and viewed) before [2, 18–20] in both children and adults. The present study significantly extends the findings of the previous work. First, our study evaluated a more comprehensive set of enrichment strategies (gestures and pictures, with and without motor tasks) than previous studies [2, 18–20] and directly compared them to a baseline condition without enrichment as well as with each other. Second, we investigated neural representations of foreign vocabulary with an actual *translation* task during fMRI. Previous fMRI studies presented participants with old-new word-recognition tasks [2, 18] or a task in which they had to detect German words in a stream of foreign words [20]. The previously used tasks did not require that participants actually knew the meaning of the foreign vocabulary. Lastly, the correlations between classifier accuracy and behavioral enrichment benefits found in our study provide evidence that the areas identified by the classifiers are relevant for learning outcome.

Activation in sensory areas during retrieval of learned items has been reported before. According to the "reactivation hypothesis" [21], an audiovisually encoded stimulus elicits activation in both visual and auditory areas even when it is presented exclusively auditorily [21, 22]. Studies investigating the reactivation hypothesis, however, do not explain *how* the learning-specific representations affect behavioral performance [21, 22]. One potential explanation is that differential activation for enrichment and no-enrichment words would be based on mental imagery while the translation is completed by other areas. This explanation, however, is unlikely. First, the correlations between enrichment benefits and classifier accuracy found in our study indicate that not only are the sensory and motor areas *reactivated* during translation but that the *improvement* of learning outcome after learning with enrichment may originate from activation in these areas. Second, there was a lack of alternative areas that could support the behavioral enrichment benefit. In previous studies, only frontal lobe areas were consistently found to be involved in translation tasks for foreign language words (see [17] for a review). In our study, we tested for involvement of such candidate areas (see Table S3), and we did not find consistent significant classification accuracy or correlations between classifier and measurements of behavioral performance. Based on the lack of alternative areas, the most parsimonious explanation is that the benefits due to enrichment are supported by representations in the visual and motor areas. This explanation also integrates well with findings in other domains [23–25]. In particular, it integrates well with research into the representation of words in the native language. Lewis and Poeppel [26], for example, demonstrated that native language words with a high amount of visual associations (such as the word "apple") can elicit responses in visual areas even before the lexical access to the word is complete, suggesting that sensory areas are involved in the early analyses of words and not only in late imagery processes. Hauk et al. [24] showed that hearing action words activated the motor cortex somatotopically, and Pulvermuller et al. [27] demonstrated that these activations are behaviorally relevant: inhibitory transcranial magnetic stimulation applied to arm- and leg-motion-controlling parts of the motor cortex led to slower recognition of words referring to arm and leg motion, respectively. Our results are in line with these studies and significantly extend them. First, we showed that life-long experience with words and the related motor output or visual associations is not necessary in order to establish representations of auditory words in visual and motor cortices. Instead, a comparably

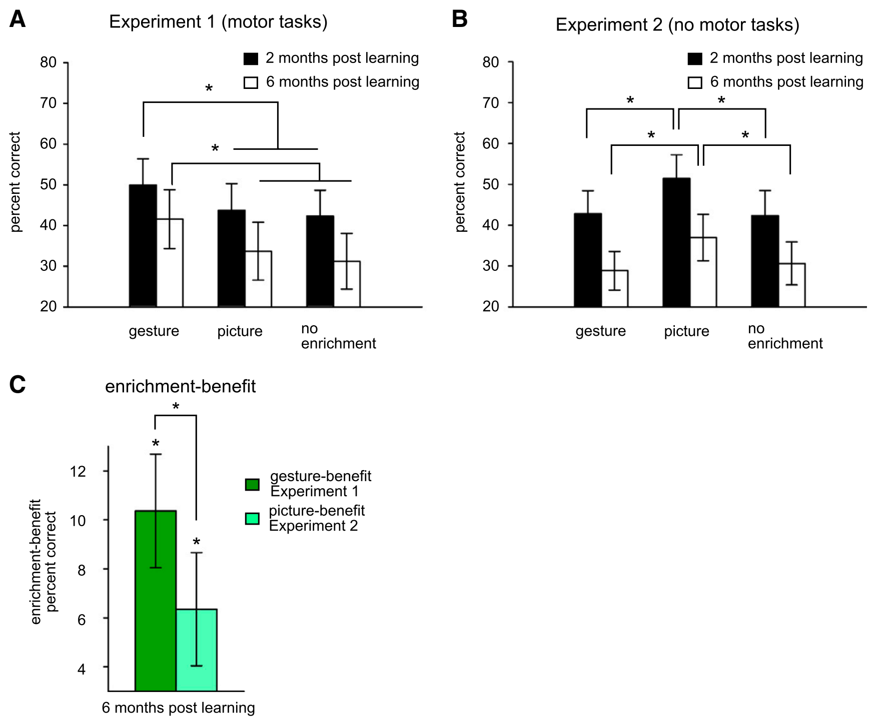

Figure 3. Results of the Paper-and-Pencil Translation Tasks

(A) Experiment 1 (motor tasks).

(B) Experiment 2 (no motor tasks).

(C) The benefit of self-performed gestures (dark green) is significantly larger than the benefit of viewed pictures (light green). We calculated the benefit as the difference between the percent correct in the enriched condition (i.e., self-performed gestures or viewed pictures) minus the percent correct in the no-enrichment condition. Error bars indicate ±1 SEM. $^*p < 0.05$. Note that only the results of the paper-and-pencil translation tasks are shown here; for discussion of the free-recall task results, see the Supplemental Results. See also Figures S1 and S3.

short learning week can be sufficient to create such representations. Second, our study revealed that representation of words occurs in highly specialized visual cortices, i.e., bmSTS and LOC. Third, our results highlight that words can also be represented in the motor and visual cortex even if their semantics are not related to actions or vision. None of the foreign words were assigned to German words that described an action or a body part. In addition, the experiment included not only concrete but also abstract nouns; abstract nouns usually do not have visual associations.

Previous research into the neural representations of foreign languages showed that knowing foreign languages can also affect the brain anatomy at a structural level. Mechelli et al. [28] showed that proficiency in a foreign language depended on the age of acquisition and was correlated with gray-matter density in the left parietal cortex. Moreover, Schlegel et al. [29] investigated white matter during intensive learning of Chinese as a foreign language. They revealed changes in measures of white-matter integrity during the course of learning. Whether cortical changes at the structural level also occur after short learning procedures with enrichment as used in the present study is currently unknown.

In summary, our results imply that the better outcome for foreign word learning with enrichment can be explained by the recruitment of sensory and motor networks. This is in accordance with the multisensory learning theory [3, 4]. For teaching practice, the results suggest that using self-performed gestures during vocabulary learning is the better strategy for long-term vocabulary knowledge than the commonly practiced learning with pictures.

Supplemental Information

Supplemental Information includes Supplemental Results, Supplemental Discussion, Supplemental Experimental Procedures, three figures, and five tables and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2014.11.068.

Author Contributions

K.M.M., M.M., and K.v.K. designed the study. K.M.M. and M.M. created the stimuli. K.M.M. collected the data. K.M.M. and I.B.Y. analyzed the data. K.M.M., I.B.Y., M.M., and K.v.K. wrote the manuscript.

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References

1. Chun, D.M., and Plass, J.L. (1996). Effects of multimedia annotations on vocabulary acquisition. Mod. Lang. J. *80*, 183–198.
2. Macedonia, M., Müller, K., and Friederici, A.D. (2011). The impact of iconic gestures on foreign language word learning and its neural substrate. Hum. Brain Mapp. *32*, 982–998.
3. Shams, L., and Seitz, A.R. (2008). Benefits of multisensory learning. Trends Cogn. Sci. *12*, 411–417.
4. von Kriegstein, K., and Giraud, A.-L. (2006). Implicit multisensory associations influence voice recognition. PLoS Biol. *4*, e326.
5. Jastorff, J., Kourtzi, Z., and Giese, M.A. (2006). Learning to discriminate complex movements: biological versus artificial trajectories. J. Vis. *6*, 791–804.
6. Mayer, K.M., and Vuong, Q.C. (2013). Automatic processing of unattended object features by functional connectivity. Front. Hum. Neurosci. *7*, 193.
7. Flowerdew, J., and Miller, L. (2005). Second Language Listening: Theory and Practice (Cambridge University Press).
8. Chang, C.-C., and Lin, C.-J. (2011). LIBSVM: a library for support vector machines. ACM Trans. Intell. Syst. Technol. *2*, 27.

9. Haynes, J.-D., and Rees, G. (2006). Decoding mental states from brain activity in humans. Nat. Rev. Neurosci. *7*, 523–534.
10. Haxby, J.V., Gobbini, M.I., Furey, M.L., Ishai, A., Schouten, J.L., and Pietrini, P. (2001). Distributed and overlapping representations of faces and objects in ventral temporal cortex. Science *293*, 2425–2430.
11. Kriegeskorte, N., Goebel, R., and Bandettini, P. (2006). Information-based functional brain mapping. Proc. Natl. Acad. Sci. USA *103*, 3863–3868.
12. Plass, J.L., Chun, D.M., Mayer, R.E., and Leutner, D. (1998). Supporting visual and verbal learning preferences in a second-language multimedia learning environment. J. Educ. Psychol. *90*, 25.
13. Craik, F.I.M., and Lockhart, R.S. (1972). Levels of processing - framework for memory research. J. Verbal Learning Verbal Behav. *11*, 671–684.
14. Nyberg, L. (2002). Levels of processing: a view from functional brain imaging. Memory *10*, 345–348.
15. Hyde, T.S., and Jenkins, J.J. (1973). Recall for words as a function of semantic, graphic, and syntactic orienting tasks. J. Verbal Learning Verbal Behav. *12*, 471–480.
16. Vigneau, M., Beaucousin, V., Hervé, P.Y., Duffau, H., Crivello, F., Houdé, O., Mazoyer, B., and Tzourio-Mazoyer, N. (2006). Meta-analyzing left hemisphere language areas: phonology, semantics, and sentence processing. Neuroimage *30*, 1414–1432.
17. Garcia, A.M. (2013). Brain activity during translation: a review of the neuroimaging evidence as a testing ground for clinically-based hypotheses. J. Neurolinguistics *26*, 370–383.
18. Kelly, S.D., McDevitt, T., and Esch, M. (2009). Brief training with co-speech gesture lends a hand to word learning in a foreign language. Lang. Cogn. Process. *24*, 313–334.
19. Tellier, M. (2008). The effect of gestures on second language memorisation by young children. Gesture *8*, 219–235.
20. Krönke, K.M., Mueller, K., Friederici, A.D., and Obrig, H. (2013). Learning by doing? The effect of gestures on implicit retrieval of newly acquired words. Cortex *49*, 2553–2568.
21. Wheeler, M.E., Petersen, S.E., and Buckner, R.L. (2000). Memory's echo: vivid remembering reactivates sensory-specific cortex. Proc. Natl. Acad. Sci. USA *97*, 11125–11129.
22. Nyberg, L., Habib, R., McIntosh, A.R., and Tulving, E. (2000). Reactivation of encoding-related brain activity during memory retrieval. Proc. Natl. Acad. Sci. USA *97*, 11120–11124.
23. von Kriegstein, K., Dogan, O., Grüter, M., Giraud, A.-L., Kell, C.A., Grüter, T., Kleinschmidt, A., and Kiebel, S.J. (2008). Simulation of talking faces in the human brain improves auditory speech recognition. Proc. Natl. Acad. Sci. USA *105*, 6747–6752.
24. Hauk, O., Johnsrude, I., and Pulvermüller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. Neuron *41*, 301–307.
25. Pitcher, D., Garrido, L., Walsh, V., and Duchaine, B.C. (2008). Transcranial magnetic stimulation disrupts the perception and embodiment of facial expressions. J. Neurosci. *28*, 8929–8933.
26. Lewis, G., and Poeppel, D. (2014). The role of visual representations during the lexical access of spoken words. Brain Lang. *134*, 1–10.
27. Pulvermüller, F., Hauk, O., Nikulin, V.V., and Ilmoniemi, R.J. (2005). Functional links between motor and language systems. Eur. J. Neurosci. *21*, 793–797.
28. Mechelli, A., Crinion, J.T., Noppeney, U., O'Doherty, J., Ashburner, J., Frackowiak, R.S., and Price, C.J. (2004). Structural plasticity in the bilingual brain: proficiency in a second language and age at acquisition affect grey-matter density. Nature *431*, 757.
29. Schlegel, A.A., Rudelson, J.J., and Tse, P.U. (2012). White matter structure changes as adults learn a second language. J. Cogn. Neurosci. *24*, 1664–1670.